THERMAL & FLUIDS ANALYSIS WORKSHOP

GSFC · 2015

Performance Characterization of a Small Turbojet Engine Platform for an Engine-Integrated Solid Oxide Fuel Cell System

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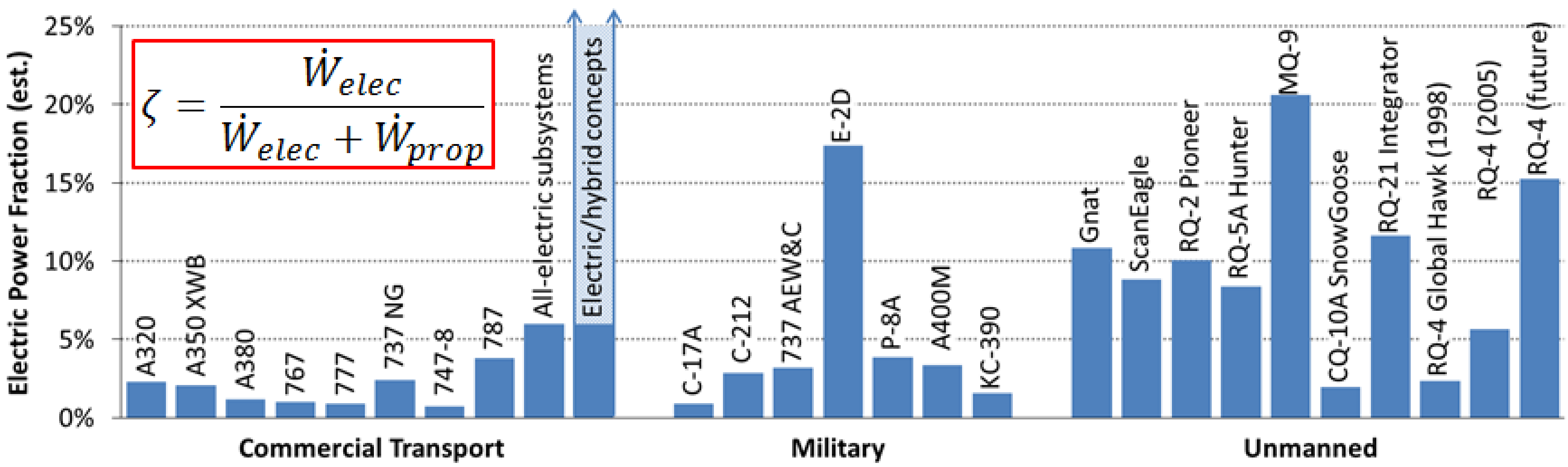
Outline

- Motivation
- Previous Work
- Objective
- Approach
- Progress
- Next Steps

Electric Power on Aircraft

- Electric power demands on aircraft are increasing
  - More electric subsystems (replace hydraulic systems with electric, etc.)
  - More electrically intensive payloads (especially UAVs)
  - Serious consideration being given to future ‘all electric’ aircraft
- Impact on fuel consumption is becoming important



Electric Power on Aircraft

- As ζ increases, efficiency of electrical power generation has greater impact on vehicle range and endurance
  - Especially true for UAVs which have high electrical power requirements and relatively low propulsive power demands
- Most modern aircraft meet electrical demands using mechanical generators driven by the main propulsive engine(s) or stand-alone auxiliary power units (APUs)
  - Both methods are relatively inefficient because they are driven by heat engines

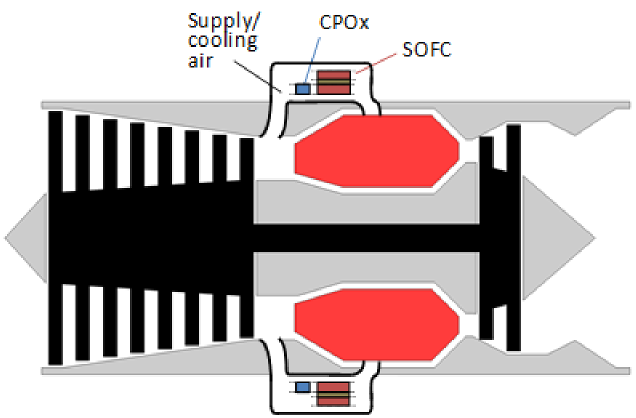
Fuel Cells

- Fuel cells offer more direct and efficient means of converting fuel energy to electric power
  - 50-60% in systems without heat recovery cycles [1] vs. 20-40% for typical gas turbine [2,3]
- Disadvantage:
  - Require complex system of pumps, blowers, sensors, controllers ('balance of plant')
    - Add complexity, cost, and mass
    - Extra mass substantially lowers specific power
      - Order of hundreds of W/Kg for stand-alone fuel cell vs. thousands of W/Kg for heat engine
    - Reduce efficiency advantage of electrochemical generation

Gas Turbine-Integrated Solid Oxide Fuel Cell

- Integrating a catalytic partial oxidation reactor (CPOx) and solid oxide fuel cell (SOFC) with a gas turbine is a promising solution to the balance of plant problem
  - GT provides air to SOFC, eliminating blowers / pumps
  - GT air is pressurized, allowing higher efficiency and power density than atmospheric pressure FCs
  - Heat losses from CPOx and SOFC are captured by bypass air in the FC duct and directed back through the Brayton cycle
  - Unreacted fuel from the SOFC is directed into the GT combustor to contribute to the Brayton cycle

GT-SOFC



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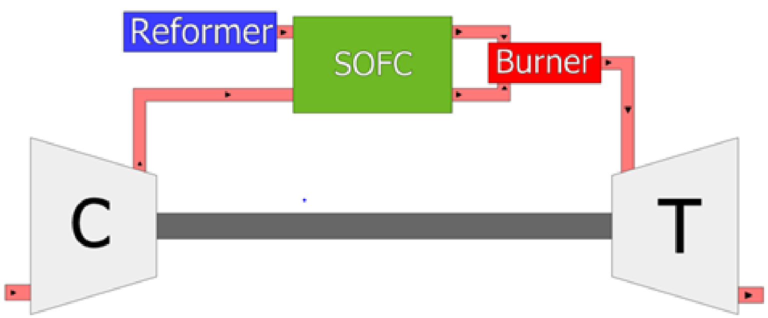
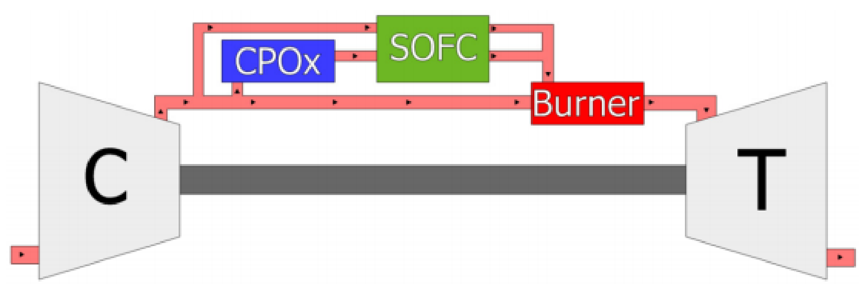
Literature Review

- Stationary terrestrial power generation applications
- Airborne applications
  - APU: designed as direct replacement for existing APU technology
  - High altitude (50-70 kft), very long endurance (days to weeks)
    - Places premium on system efficiency

Typical layout in previous studies



Layout in UMD model



Literature Review: Summary

Ground based:

Reference	Platform	Size	Reformer / FC	Fuel	FC model	GT model	Efficiency	Notes
Calise et al. [42]	MATLAB	1.5 MW	IR-SOFC	natural gas	validated against data	scaled performance maps	$\eta_{elec} = 68\%$, $\eta_{sys} > 90\%$	cost optimization
Haseli et al. [43]	MATLAB	2.4 MW	IR-SOFC	methane	zero-D	constant efficiencies	$\eta_{sys} = 60\%$	focus on the irreversibilities
Abbasi and Jiang [44]		132 kW	IR-SOFC		zero-D	constant efficiencies		power conditioning; transient response
Chan and Tian [45]		2.1 MW	IR-SOFC	natural gas	zero-D, validated against data	constant efficiencies	$\eta_{elec} = 62\%$ $\eta_{sys} = 84\%$	
Palsson et al. [46]	Aspen Plus	500 kW	pre-reformer, SOFC	methane	2-D, validated against literature	Aspen Plus std. models	$\eta_{elec} = 60\%$ $\eta_{sys} = 86\%$	combined power and heat generation
Costamagna et al. [47]	MATLAB	300 kW	steam reformer, SOFC	natural gas	zero-D	performance maps	$\eta_{sys} > 60\%$	on- and off-design analysis
Lim et al. [48]	Experiment	5 kW	pre-reformer, SOFC	natural gas				working GT-SOFC
Suther et al. [49]	Aspen Plus		steam reformer, SOFC	syngas	zero-D	Aspen Plus std. models		
Zhao et al. [50]	MATLAB			coal syngas	zero-D	ideal GT	$\eta_{sys} = 50\text{-}60\%$	
Leto et al. [51]	IPSE Pro	140 kW	IR molten carbonate	natural gas	zero-D	IPSE Pro std. models	$\eta_{sys} = 60\text{-}70\%$	
Veyo et al. [52]		300 kW, 1 MW		natural gas			$\eta_{sys} = 59\%$	

APUs:

Reference	Platform	Size	Reformer / FC	Fuel	FC model	GT model	Efficiency	Notes
Freeh et al. [54]	NPSS	200 kW	steam reformer, SOFC	Jet-A	zero-D,validated against data	performance maps	$\eta_{sys} = 40\%$, $\eta_{elec} = 65\%$	
Steffen et al. [56]	NPSS	440 kW, 1396 kg	steam reformer, SOFC	Jet-A	zero-D	performance maps	$\eta_{sys} = 62\%$	
Freeh et al. [57]	NPSS	440 kW	steam reformer, SOFC	Jet-A	zero-D	performance maps	$\eta_{sys} = 73\%$	on- and off-design analysis
Eelman et al. [58]	MATLAB	370 kW	steam reformer, PEM and SOFC	jet fuel			SOFC: $\eta_{sys} > 70\%$ PEM: $\eta_{sys} > 35\%$	aircraft integration approaches
Rajashekara et al. [59]		440 kW, >880 kg	steam reformer, SOFC	jet fuel	zero-D		SL: $\eta_{sys} = 61\%$ cruise: $\eta_{sys} = 74\%$	
Braun et al. [60]	UTRC proprietary	300 kW	autothermal reforming SOFC	Jet-A			SL: $\eta_{sys} = 53\%$ cruise: $\eta_{sys} = 70\%$	

All-electric:

Reference	Platform	Size	Reformer / FC	Fuel	FC model	GT model	Efficiency	Notes
Himansu et al. [61]	MATLAB	20 kW, 50 kW	SOFC	H_2	zero-D	constant efficiencies		
Aguiar et al. [62]		140 kW	SOFC	H_2		constant efficiencies	single: $\eta_{sys} = 54\%$ multi: $\eta_{sys} = 66\%$	multiple stacks: fuel in parallel, air in series

Previous Work at UMD

- Integrated GT-SOFC concept is very promising
  - Developed most advanced CPOx and SOFC models for GT-SOFC studies [4]
  - Produced first advanced system modeling tool for GT-SOFC integrations for combined propulsion **AND** electrical power on A/C [4]
  - Large reductions in fuel consumption relative to GT-generator systems are thermodynamically possible [5]
  - GT-SOFC can produce more electrical power than GT-generator because of TIT limits [5]

UMD Publications

Journal:

1. Waters, Cadou. “Influence of Flow Path Configuration on Gas Turbine - Solid Oxide Fuel Cell Systems for Aircraft Propulsion and Power”. In preparation, 2015.
2. Waters, Cadou. “Engine-Integrated Solid Oxide Fuel Cells for Efficient Electrical Power Generation on Aircraft”. Journal of Power Sources, 284, 2015.
3. Waters, Cadou. “Estimating the neutrally buoyant energy density of a Rankine-cycle/fuel-cell underwater propulsion system”. Journal of Power Sources, 248, 2014.
4. Waters, Cadou. “Modeling a hybrid Rankine-cycle/fuel-cell underwater propulsion system based on aluminum-water combustion”. Journal of Power Sources, 221, 2013.
5. Waters, Cadou, Eagle. “Quantifying Unmanned Undersea Vehicle Range Improvement Enabled by Aluminum–Water Power System”. Journal of Propulsion and Power, 29, 2013.
6. Waters, Cadou. “Development of a Low-Cost Millinewton Thrust Stand”. In preparation.

Conference:

1. Waters, Vannoy, Cadou. “Influence of Flow Path Configuration on the Performance of Hybrid Turbine - Solid Oxide Fuel Cell Systems for Aircraft Propulsion and Power”. Joint Propulsion Conference, Orlando, FL, 2015. *Abstract accepted.*
2. Waters, Cadou. “Optimization of Gas Turbine - Solid Oxide Fuel Cell Systems for Aircraft Power Generation”. Aerospace Sciences Mtg., Kissimmee, FL, 2015.
3. Waters, Cadou. “Engine-Integrated Solid Oxide Fuel Cells for Efficient Electrical Power Generation on Aircraft”. Aerospace Sciences Mtg., National Harbor, MD, 2014.
4. Waters, Cadou. “Modeling a Hybrid Rankine-Cycle/SOFC UUV Propulsion System Powered by Aluminum-Water Combustion”. Aerospace Sciences Mtg., Nashville, 2012.
5. Eagle, Waters, Cadou. “System Modeling of a Novel Aluminum Fueled UUV Power System”. Aerospace Sciences Mtg., Nashville, 2012.

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Objective

- Begin process of experimental validation by developing a small, laboratory-scale hybrid GT-SOFC prototype at a scale suitable for a small UAV
  - Confirm experimentally the performance advantage of integrated GT-SOFC system predicted by existing numerical model
  - Validate model and develop optimized integration strategies for larger platforms

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Approach

- Select an appropriate engine – AMT Olympus
- Develop a model of the system in NPSS
- Measure engine performance on thrust stand
  - Calibrate NPSS model
  - Confirm range of possible FC operating parameters (flow rate, gas Temp., etc.)
- Add CPOx/SOFC model to engine system model
  - Use previously developed fuel cell models
  - Hopefully, we will be able to identify a suitable off-the-shelf FC stack
- Modify engine to incorporate the FC stack
- Test integrated system

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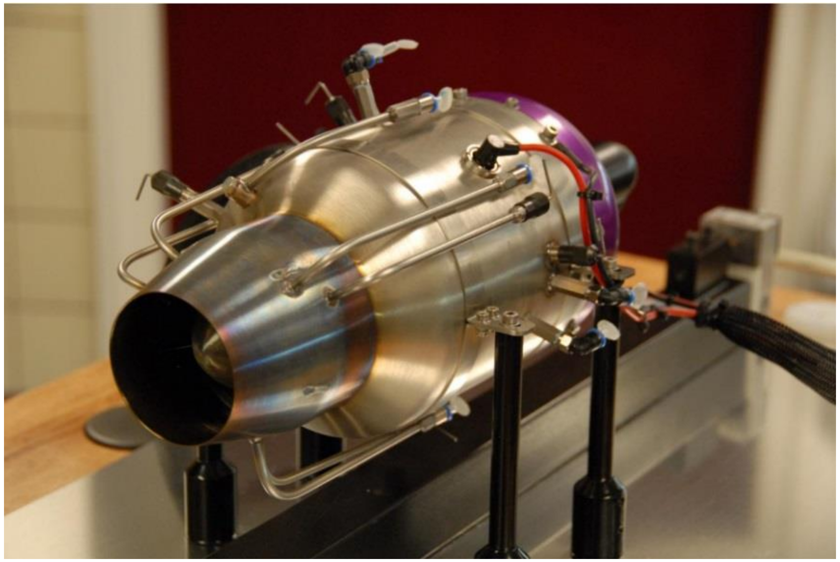
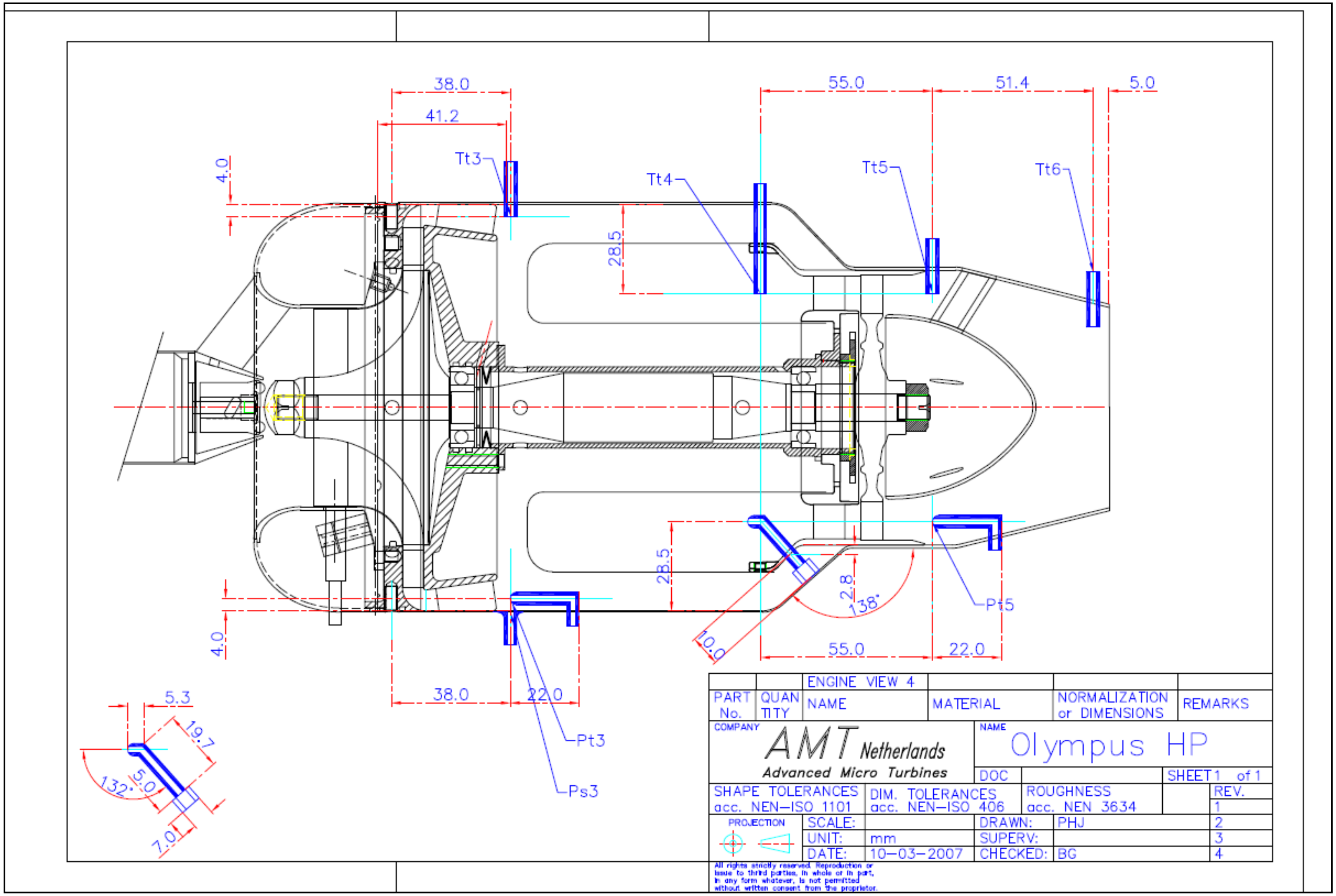
Platform Selection

- AMT Olympus in 'University Configuration'
  - Small (50 lb thrust class) turbojet engine
  - Factory-installed temperature/pressure measuring points
  - Compressor performance map available

http://www.amtjets.com/pdf/University-Olympus-HP-Jan-2013.pdf



AMT Olympus



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ENGINE VIEW 4
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Reasons for Selecting AMT Engine

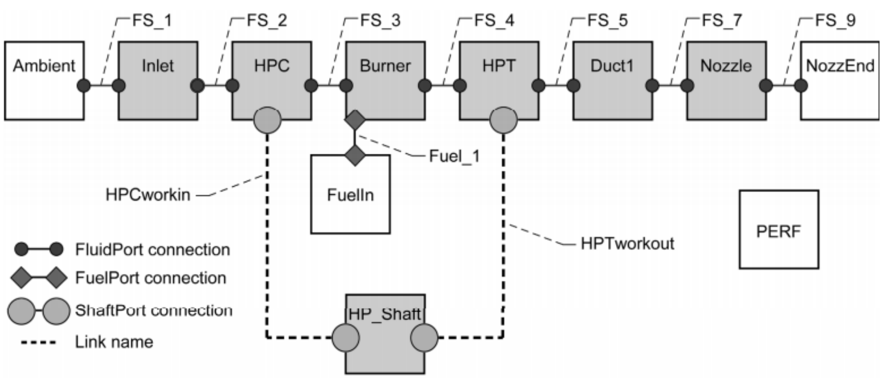
- Indoor facilities limited to engines <= 200 lb thrust
- Availability of pre-installed measurement ports
  - Significant time savings
  - Limits risk of tampering with flow path
- Availability of compressor map
  - Needed for modeling effort but most companies won’t divulge
  - One less thing to measure
- Other performance data are also available
  - Prof. Harald Funke – Aachen University of Applied Sciences, Aachen, Germany

Numerical Propulsion System Simulation

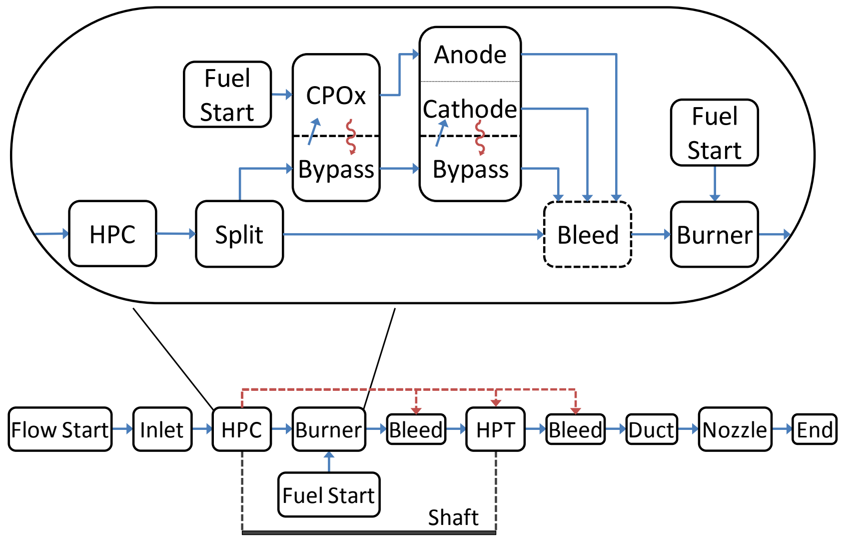
- Modeling in this work is implemented in the framework of Numerical Propulsion System Simulation (NPSS)
- NPSS was developed by NASA to simulate gas turbine engines (but equally applicable for many thermodynamic systems)
- Built in quasi-Newton method solver
- Multiple built in thermodynamics packages (including chemical equilibrium, via CEA)
- System models are assembled from ‘elements’
  - Library of ‘standard’ pre-made GT components
  - Incorporates user defined components written in object oriented programming language
- An emerging standard in Aerospace simulation (used by major engine manufactures, NASA, DoD)

System Model

NPSS Turbojet Model without CPOx/SOFC [6]



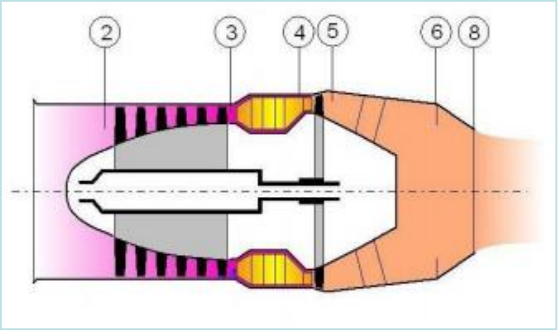
NPSS Turbojet Model with CPOx/SOFC [5]



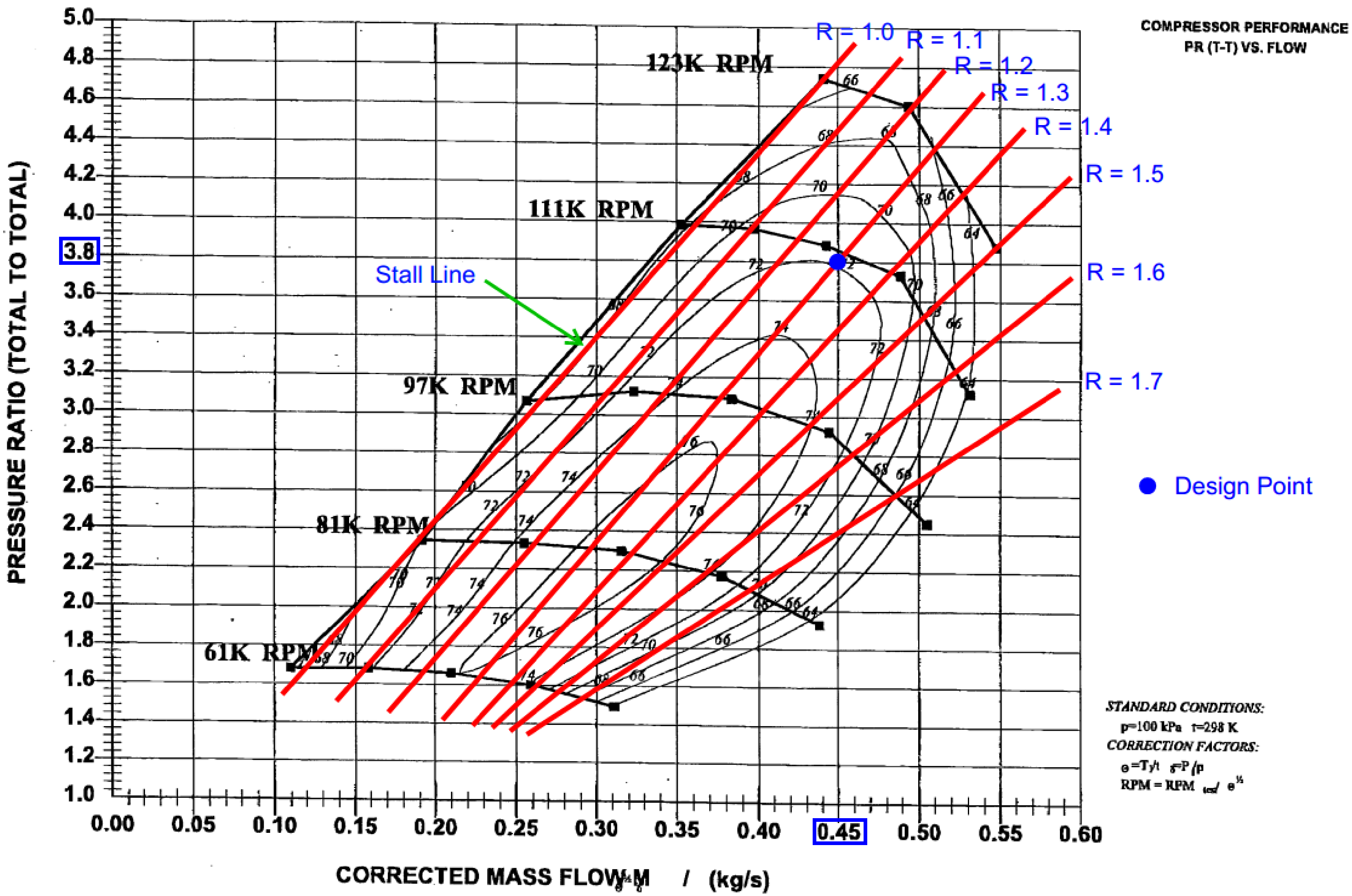
NPSS Thermodynamic Model of Olympus

Design Conditions (Full Throttle)	
RPM	108,500
Air Flow Rate (lbm/sec)	0.99
Compressor Total Pressure Ratio (P_{03}/P_{02})	3.8
Compressor Efficiency	0.72
Fuel Type	Jet A
Q_{LHV} (BTU/lbm)	18486.7
Fuel Flow Rate (lbm/sec)	0.0235
Turbine Total Pressure Ratio (P_{04}/P_{05})	2.098
Turbine Efficiency	0.80

- Using compressor map provided by AMT
- Using low pressure turbine map provided with NPSS software [7]
- Comparing NPSS temperature and pressure predictions at axial stages along engine to experimental data provided by Prof. Funke



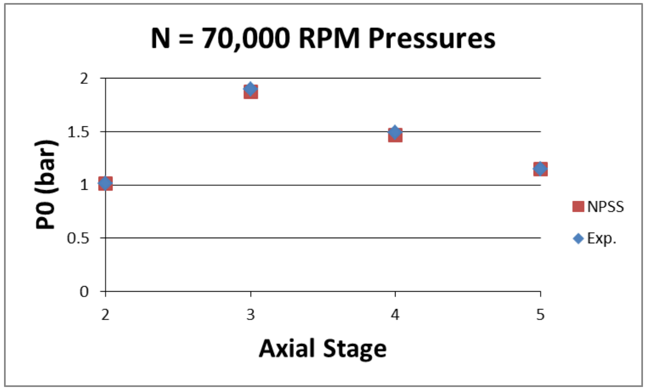
Olympus Compressor Map

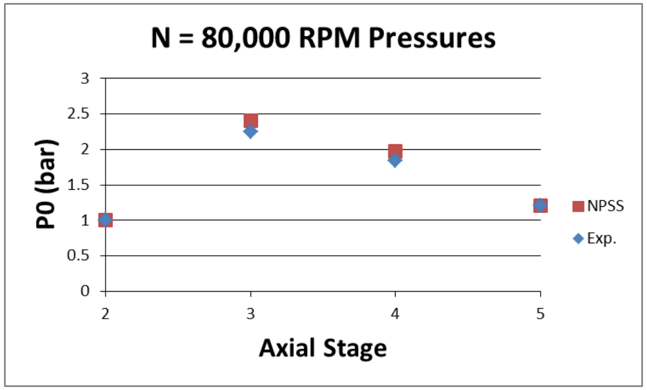


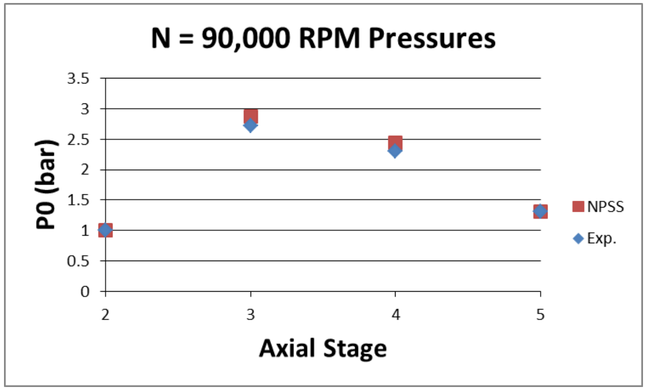
Olympus Turbine Map

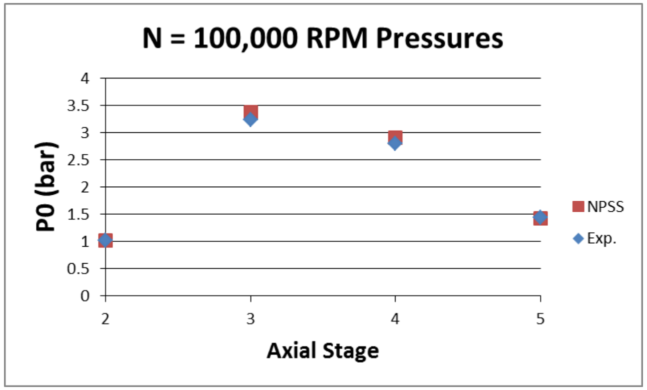
- Turbine map for Olympus is unavailable
  - Neither AMT nor Prof. Funke could provide map
- As a result, we are using a low pressure turbine map provided with NPSS [7]
  - NPSS scales the map linearly in three axes [8] based on the input design conditions
  - Turbine design efficiency of 0.80 was chosen to match the measured performance

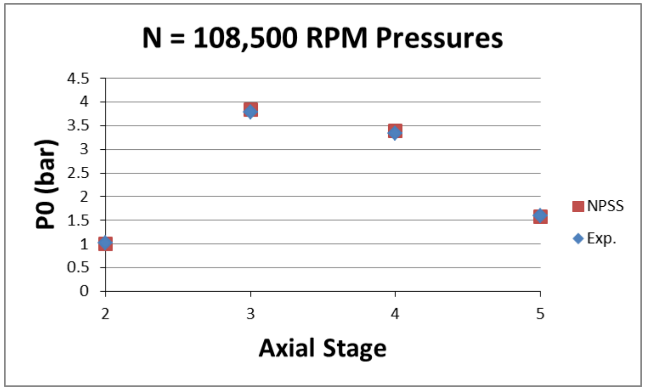
Axial Stage Pressures

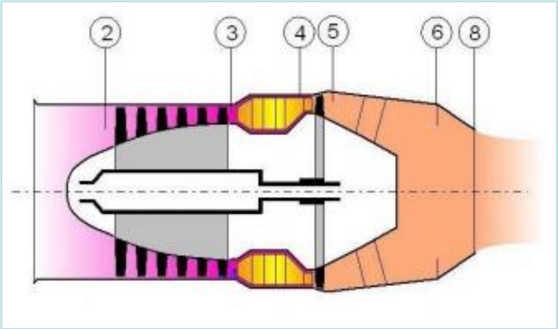




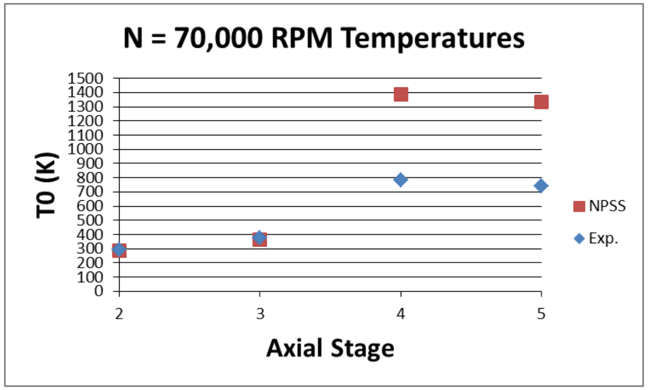


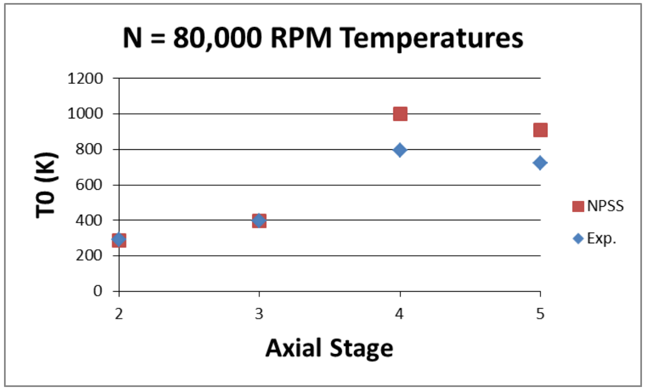


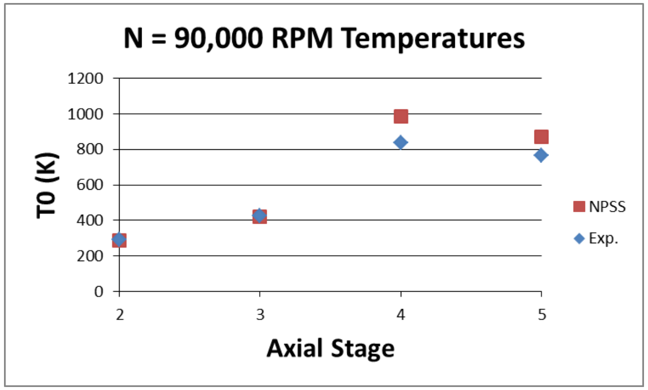


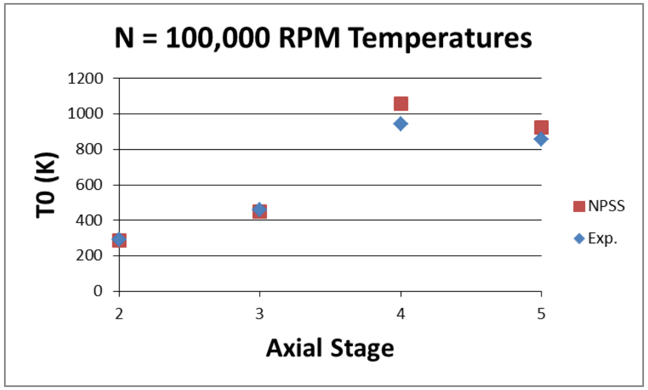


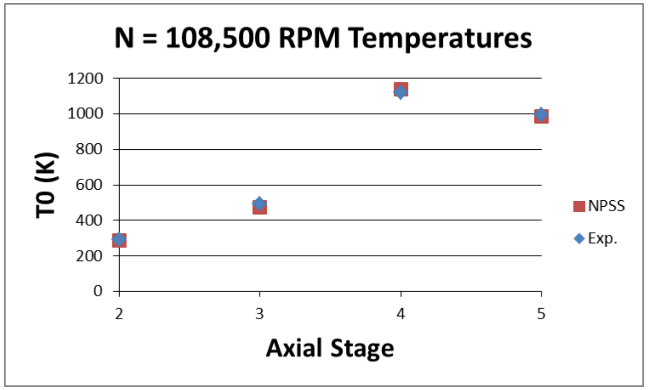
Axial Stage Temperatures

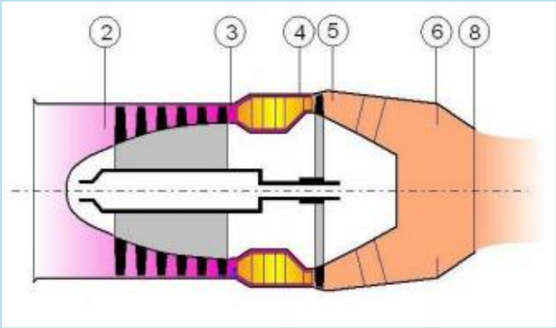






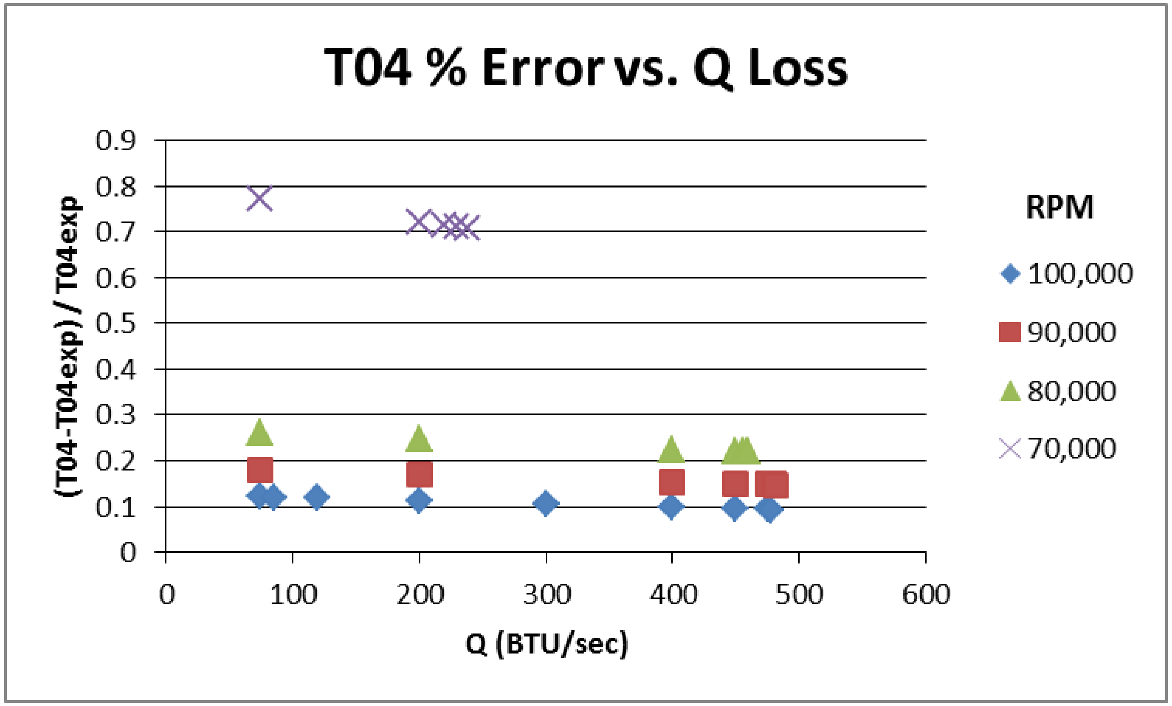






Combustor Heat Loss

- Is temperature discrepancy caused by heat loss?

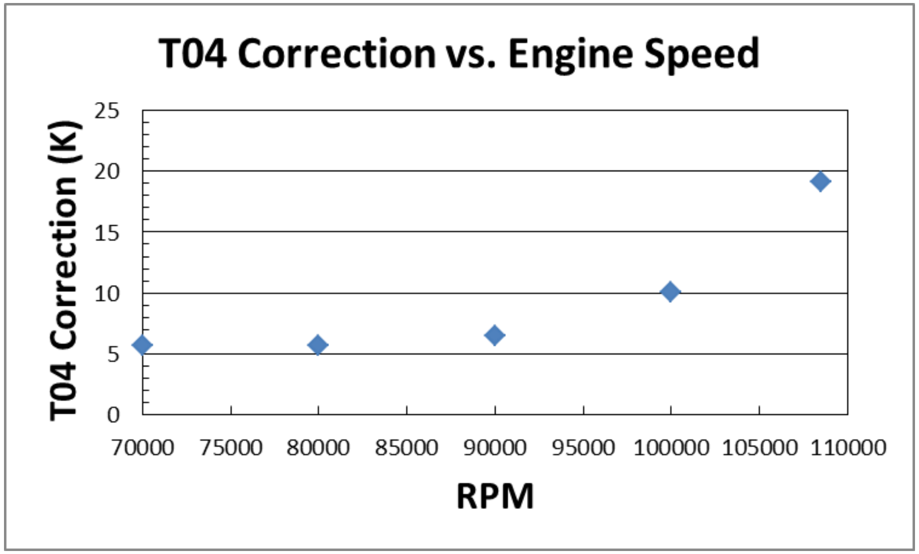


- No
  - Little reduction in discrepancies in T_{04} predictions as Q increases
  - Unable to converge if heat loss is too large

Why does NPSS not converge?

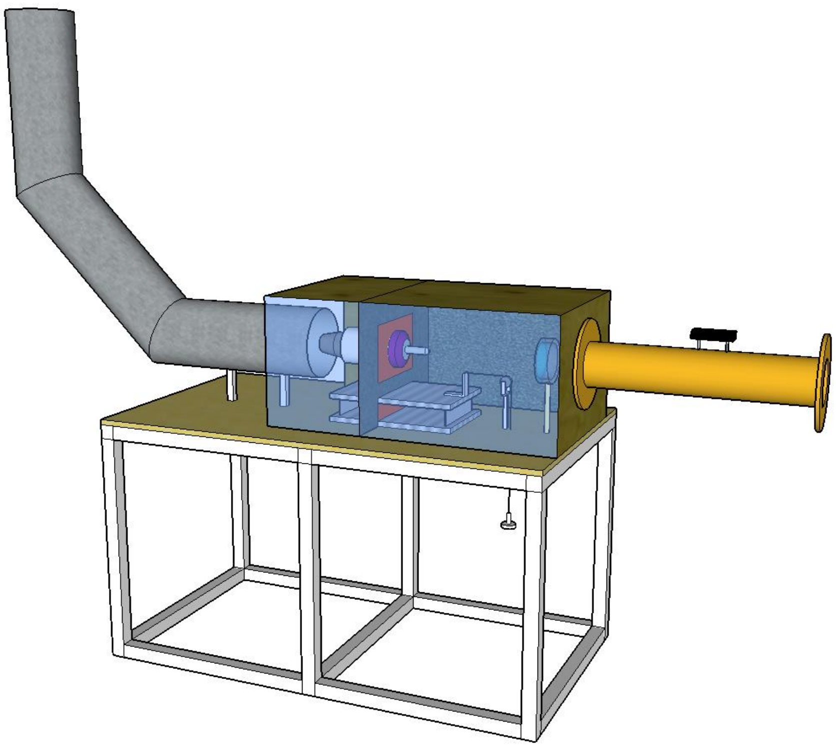
- Turbine design parameters are on the edge of unscaled turbine map
  - Design turbine pressure ratio (P_{04}/P_{05}) is about 2.0; the lowest pressure ratio on unscaled map is 2.0
    - NPSS likely having issues when it must interpolate/extrapolate values based on pressure ratios lower than 2.0
- Will be able to generate turbine performance map for Olympus from our own experimental measurements
- Still investigating source of NPSS solver's inability to converge on solution with added heat loss in combustor

T_{04} Radiation Corrections



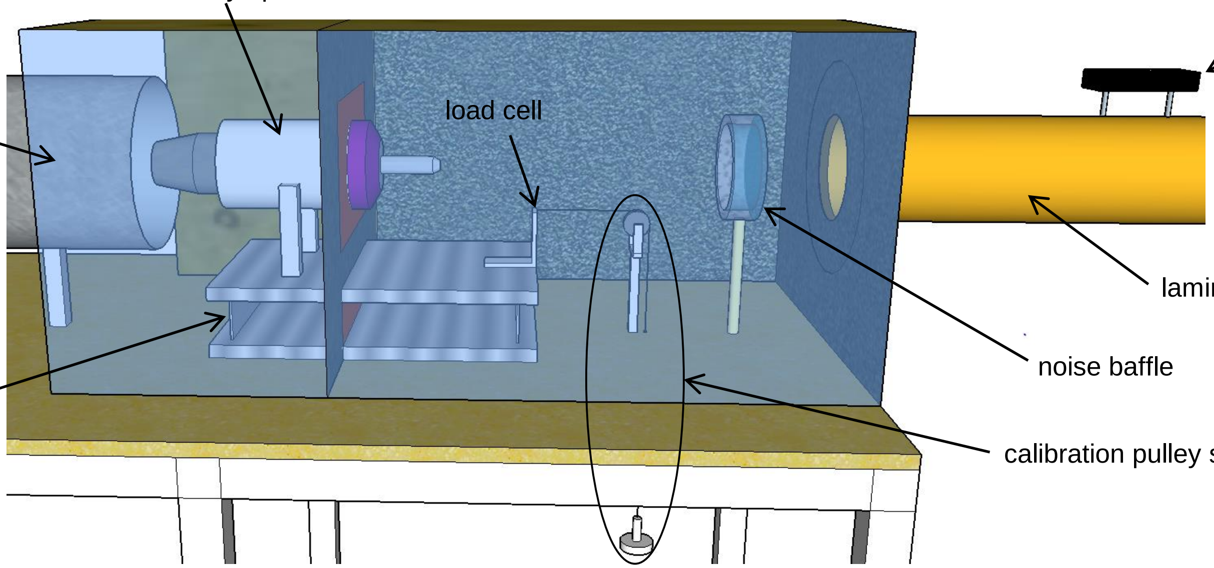
- Checked radiation correction to see if this is a contributing factor to T_{04} discrepancy
  - Preliminary results indicate no
  - Apply conduction correction next
- Likely main causes
  - Wrong turbine efficiency
  - Unrealistic combustion model (need to incorporate multi-species and $C_p(T)$)

Preliminary Noise Box Design



- Need acoustic/containment housing for engine for safe operation and to accommodate modifications to engine
- Box made from plywood
  - Rigid in case of catastrophic engine failure
- Interior walls insulated with sound-proofing material (fire-proof denim insulation)
- Consideration
  - How to seal dividing wall over compressor end of engine and thrust stand

Preliminary Noise Box Design



- Thrust stand calibrated with known weights on pulley system
- 'noise baffle' used to absorb sound waves from compressor
  - Needs to be sufficiently large enough to absorb sound but small enough to prevent significant obstruction of airflow
- Incoming airflow will be directed through single inlet so flow rate can be measured with laminar flow element

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Next Steps

- Complete construction of acoustic housing
- Make measurements and calibrate NPSS model
  - Generate own turbine map
- Incorporate fuel cell elements into NPSS model
- Identify suitable off-the-shelf FC stack for integration
- Use NPSS model to predict performance of integrated Olympus-SOFC system
- Begin physical integration

Acknowledgements

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  - Patuxent Naval Air Station: Technical monitor Sean Field
  - Office of Naval Research: Technical monitor Sarwat Chappell
- Thanks also to:
  - Prof. Greg Jackson of the Colorado School of Mines for help with fuel cell modeling
  - Tom Lavelle (NASA) for help getting started with NPSS

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